An Energy and Carbon Life Cycle Assessment of Tidal Power Case Study: the Proposed Cardiff-Weston Severn Barrage Scheme

K A Kelly[1,*], **M C McManus**[1,2] and **G P Hammond**[1,2]

[1]Department of Mechanical Engineering, University of Bath, Bath, BA2 7AY, UK
[2]Institute for Sustainable Energy and the Environment, University of Bath, Bath, BA2 7AY, UK

Keywords: Tidal barrage; life cycle assessment; low carbon energy.

ABSTRACT:
Under the Kyoto Protocol many countries have targets to reduce carbon emissions and increase renewable energy production. In order to do this effectively the impact and efficacy of differing schemes must be determined. One option for producing electricity is through the use of a tidal barrage. The largest potential barrage scheme considered in the UK is the Cardiff-Weston barrage scheme in the Severn estuary. The scheme would be a single, renewable installation and is predicted to constitute 4% of the UK electricity supply. Therefore a carbon and energy assessment was completed on the Cardiff-Weston Severn barrage scheme. The assessment shows that the energy and carbon intensity of the Severn barrage is small in comparison to the National Grid mix and that, given reasonable assumptions, the Severn barrage can contribute to meeting the UK carbon reduction target. Importantly, the operation stage was identified as both the most energy and carbon intense by a large margin. This is a notable finding as preceding studies have tended to dismiss the consequences of the barrage operation as minimal or nil. Whilst these findings are for the Cardiff-Weston barrage, the implications will be similar for tidal barrages in other sites in the UK and globally.

1 INTRODUCTION

Since the introduction of the Climate Change Act [1] in 2008 and the Renewables Obligation [2] policy, the UK has been bound to reducing its national GHG emissions and to increasing its production of renewable energy. Hence exploration of ways of achieving these twin aims has become increasingly important. One method for producing relatively large quantities of energy is through marine power. The Cardiff-Weston barrage scheme for the Severn Estuary, UK, is an example of a marine power system driven by the second largest tidal range in the world.

The potential of the Severn estuary for energy generation was first explored when Lord Brabazon formed the first Severn Barrage Committee in 1925. They proposed an 800MW barrage at English Stones, which is the site of the more recent Shoots Barrage proposal but the committee disbanded in 1933 without undertaking any construction. In 1978, a second Severn Barrage Committee formed under Sir Hermann Bondi and proposed a 7200MW ebb generation scheme to stretch from Lavernock Point near Cardiff to Brean Down near Weston-Super-Mare, with an annual output of 12.9 TWh [3]. This was the start of the so-called Cardiff-Weston proposal, which is also commonly regarded as *the* Severn barrage

* Corresponding Author. tel: +44 1225 384550, e-mail: k.a.kelly@bath.ac.uk

proposal. The Severn Tidal Power Group, STPG, was formed following the publication of the Bondi report in order to complete the further work recommended by the Bondi committee. The STPG published the results of an Interim Study in 1986 and it was again recommended that further work was carried out [4]. The STPG then carried out the Severn Barrage Development Project, funded equally by the STPG, the Department of Energy and the Central Electricity Generating Board. The STPG published the 'Severn Barrage Project Detailed Report' [5], consisting of five volumes in 1989. This report remains the most comprehensive account of the proposed schemes and their feasibility with regard to the mechanical, electrical, economic and environmental constraints. The 1989 STPG report estimated that the average annual output from the barrage plant would be 17.83 TWh and put forward a barrage design and bill of materials which has provided the basis of nearly all studies completed since. In 2006 the Sustainable Development Commission, SDC, began the first ever strategic overview of tidal power in the UK [6]. The project assessed the technical, economical, social and environmental factors associated with barrage and non-barrage proposals for the Severn Estuary, however the technical study focuses on the Shoots Barrage and the Cardiff-Weston proposals [7]. Analysis completed for the study estimated that the average annual net power output would be 17 TWh to the nearest TWh. This would constitute 4% of the UK electricity supply and 0.6% of the total UK energy supply [6]. The summary report [6] states that, "The SDC believes that there is a strong case to be made for a sustainable Severn barrage." Following the completion of the project, the SDC recommendations were submitted to the UK Government and the Department of Energy and Climate Change, DECC, launched a two year feasibility study in 2008. The conclusion of the study, made public in 2010, was that there was no convincing case for any scheme at the current time. Although, it is conceded that there are circumstances in which a future Government may chose to review the case it is expected that a review would not take place before 2015 at the earliest. Hence it can be estimated that the earliest possible date that construction may begin would be around 2017, ready for full operation in 2025.

It seems the Severn Barrage scheme is a recurring proposal and, hence, adding to the knowledge base on this scheme is essential. All studies mentioned above have actually included words to this effect in their conclusions. Furthermore, if the UK is to meet its carbon reduction and/or renewable targets, then considerable technology change is inevitable. Decisions have to be made on which new technologies to invest in, in terms of energy and carbon investment as well as financial, and those decisions are best made comparatively. Even if a Severn barrage is never built, robust assessments of the proposal provide benchmarks by which to judge other schemes. Tidal barrage schemes could be implemented across UK and the rest of the globe, so an understanding of their impact is vital.

1.1 REVIEW OF EXISTING SEVERN BARRAGE ENERGY AND CARBON ANALYSES

There have been four main studies of the Severn barrage which assess either or both the energy demand and carbon footprint of the scheme, starting with Roberts who completed the first comprehensive energy accounting study in 1982 [8]. The study calculations show that the scheme which is most similar to the Cardiff-Weston barrage would have an energy ratio of 14.2:1, in a range of 12:1–16:1. Roberts' used an annual power out of only 12 TWh and the inventory data was derived almost entirely for cost estimates. The SDC's technical study [7] produced two displaced carbon emission payback periods via comparisons with, a) the UK electricity grid generation mix and b) a combined cycle gas turbine. The results are presented in Table 1.

Average Annual Energy (TWh/year)	17.00
CO_2 emissions (gCO_2/kWh)	2.42
CO_2 emissions of National Grid Mix (gCO_2/kWh)	430.00
CO_2 saved wrt to National Grid Mix (gCO_2/kWh)	427.58
[Displaced] Payback period (months)	8.16
CO_2 emissions of CCGT (gCO_2/kWh)	329.00
CO_2 saved wrt to CCGT (gCO_2/kWh)	326.58
[Displaced] Payback period (months)	10.68

Table 1 Table of Carbon Analysis Results from the SDC study [7]

A Shawater Ltd study [9] focuses almost exclusively on the embodied carbon of the barrage materials, but calculates a displaced carbon emission payback period via comparison with the operation emissions of the Drax coal-fired power station, of less than 6 months. This mismatch in life stages limits the usefulness of the study conclusions as it does not compare 'like with like'. Neither the SDC [7] nor the Shawater [9] studies make any detailed estimate for the operation life stages. A 'Technology Assessment' [10] of both the Cardiff-Western and Shoots barrage proposals was completed at the University of Bath in 2010. The study establishes likely suppliers and hence provides justified estimates for the likely transport methods and distances to site. The annual energy output is assumed to be 16.8 TWh, and is taken from the SDC study. An energy gain ratio range of 18.3:1 to 25.5:1 is calculated with an energy payback period of 8.6 years. A final carbon figure of 9.5-11.0 g of CO_2/kWh is given. The study streamlines the data available in the above literature but excludes some large areas of the life cycle because of data gaps.

This paper therefore applies a Life Cycle approach to the Severn Barrage in order to add to the knowledge base, test the assumptions made in the previous studies, and determine the overall energy and carbon balance of such a scheme. It also provides a basis for studies of similar barrage proposals both nationally and internationally.

2 LIFE CYCLE ASSESSMENT

Life Cycle Assessment, or LCA, is a way to account for the environmental burden of a given product or service across its whole lifetime, from material extraction to manufacture to use to disposal or from 'Cradle to Grave'. The ISO standards ISO 14040:2006 [11] and ISO 14044:2006 [12] state that an LCA must include the following four phases:

1. Goal and scope: this outlines the system boundary and level of detail and the intended use of the study. The depth and the breadth of LCA can differ considerably depending on the goal of a particular LCA.
2. Inventory analysis: here the data necessary to meet the goals of the defined study is collected
3. Impact assessment: The purpose of the life cycle impact assessment, LCIA, is to provide additional information to help assess a product system's life cycle inventory, LCI, results so as to better understand their environmental significance. Within the LCIA the inventory data is classified into selected environmental impacts so that their significance towards the varying impacts can be assessed
4. Results interpretation: within this stage the results of an LCI or an LCIA, or both, are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition

The structure of an LCA can be explained using the visualisation shown in Figure 1.

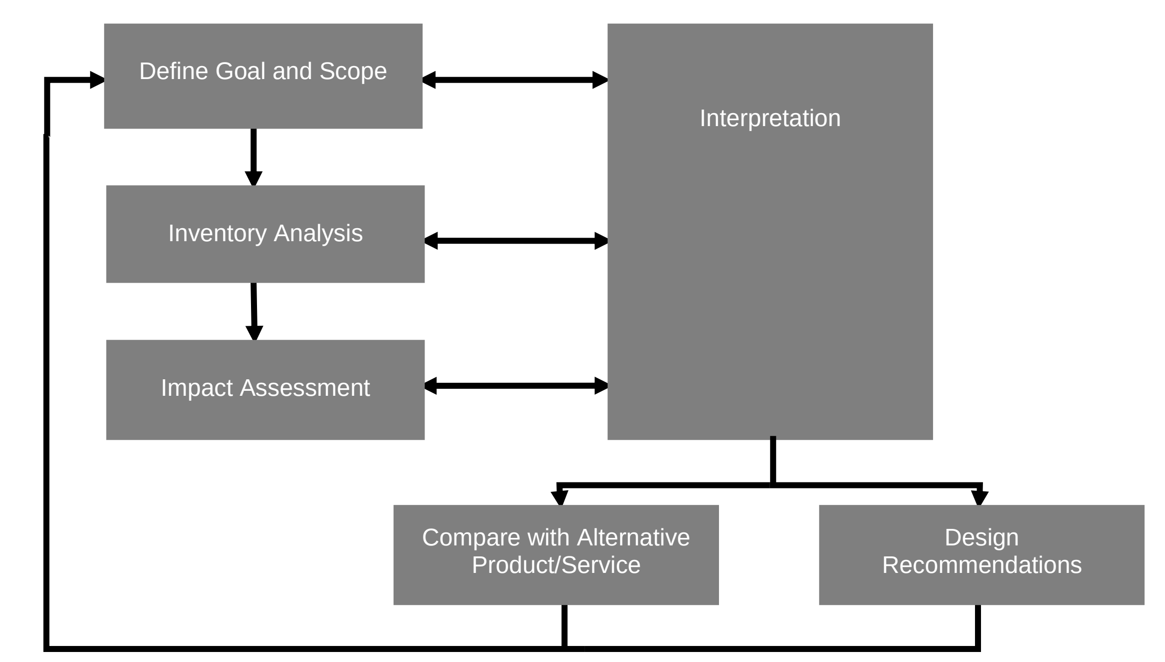


Figure 1 Visualisation of the structure of a Life Cycle Assessment

3 GOAL AND SCOPE

The study estimates the total potential energy demand and carbon burden of the proposed Cardiff-Weston Severn barrage scheme across its lifetime using LCA methodology. The LCA software package SimaPro [13] is used to organise the LCI and conduct the Impact Assessments. Within this report only the Cumulative Energy Demand and the carbon intensity or global warming potential, GWP, data are presented. The impact assessment methodologies Cumulative Energy Demand v1.07 [14] and IPCC 2007 GWP 100a (with a timeframe of 100 years) [15] were used.

It is a stream lined study as the LCI data, life cycle inventory, is based on and largely limited to what is available from existing technical and economic assessments. However the study also plugs some of the data gaps previously identified and alternative representations of the critical inventory data have been developed in order to test the robustness of the assumptions made in existing assessments. Figure 2 provides a visualisation of the processes that fall within the system boundaries for the study and those that do not.

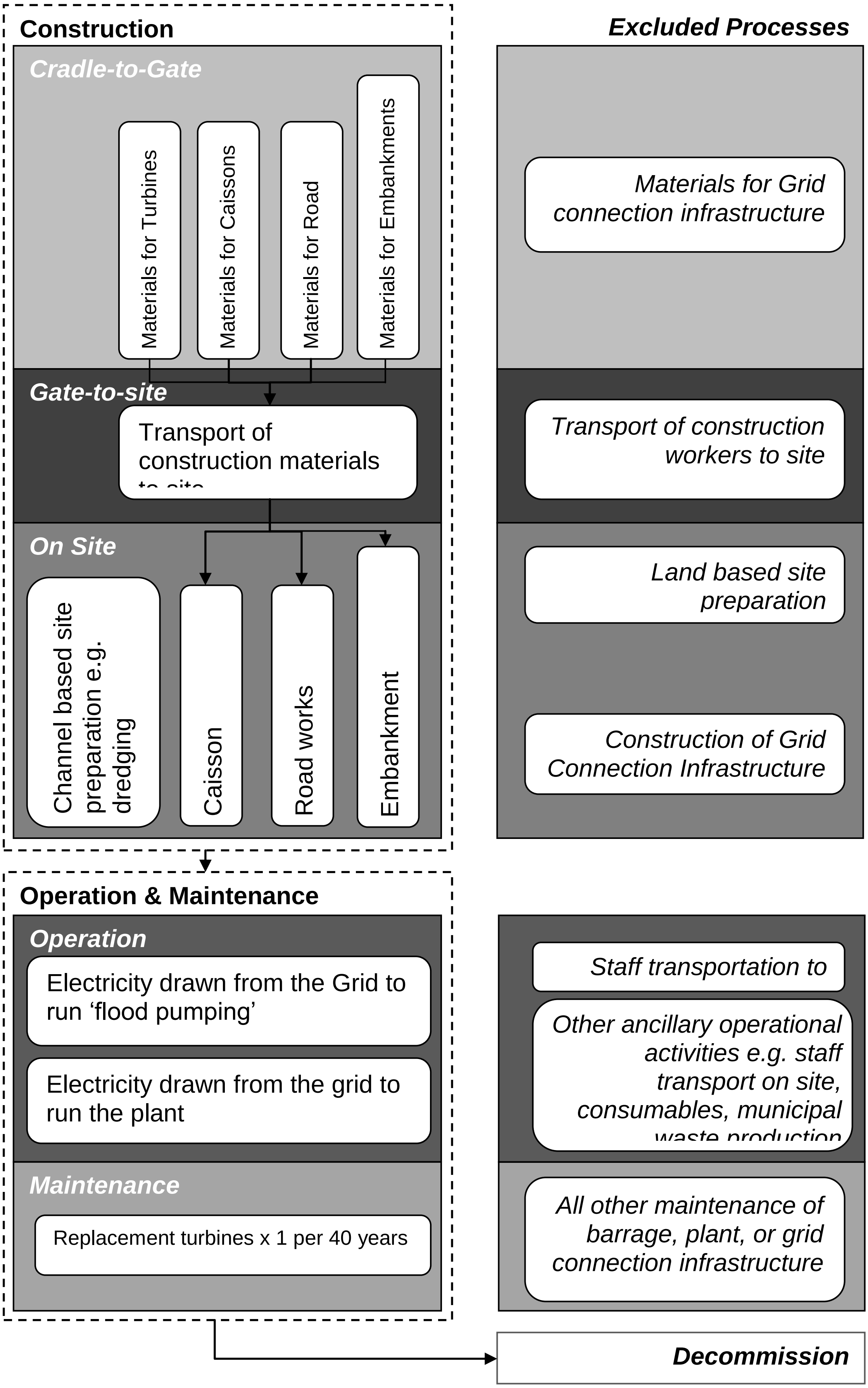


Figure 2 Flow diagram showing the system boundaries of the LCA study of the Severn barrage

Comparisons are made with the UK National Grid as it was in 1990 and 2008, and with how it potentially could be in 2050 according to the Transition Pathways research consortium. The Transition Pathways research consortium, consisting of representatives from nine UK Universities in collaboration with E.On UK and the EPSRC, have proposed three different scenarios for how the UK energy landscape will develop up to 2050 and the resultant technology mix for the UK National Grid [16]. The three scenarios can be summarised thus:

- *Central Control*: The government is the main actor. The electricity supply mix is characterized by large, centralized schemes, predominately nuclear but also including CCS, wind farms and tidal barrages.
- *Market Rules*: Industry is the main actor. The electricity supply mix is characterized by large, centralized schemes predominately CCS but also including nuclear, wind farms and tidal barrages.
- *Thousand Flowers*: Consumers/citizens are the main actors. The electricity supply mix is characterized by smaller, decentralized schemes, including gas and biomass district heating and solar. Energy efficiency and demand reduction has greatest significance in this scenario.

4 LIFE CYCLE INVENTORY

The design lifetime of the Severn barrage is 120 years [5] and can be described as consisting of the four life cycle stages of: 1) construction, 2) operation, 3) maintenance and 4) decommission.

4.1 CONSTRUCTION

The basics of the predicted construction schedule have remained largely unchanged since they were first described in detail in the STPG study, but have been subject to some refinement in more recent studies.

4.1.1 CONSTRUCTION MATERIALS

To accurately represent each construction material in the LCI, all the process stages of the up until delivery to site are considered i.e. the raw material extraction, any factory production processing and the transportation to site. To simplify the estimation task, this has been split into the two sub-stages of:

- The ‘cradle-to-(factory) gate’ stage encompasses all processes up until the material is ready to leave the factory. The material requirements as set out in the SDC[7] study were adopted and associated data for each material type was extracted from either the EcoInvent [17] or ICE [18] databases.
- The ‘(factory) gate-to-site’ stage is restricted to the transportation of construction materials to the construction site. The estimations as set out in the Spevack et al study were adopted [10]

Table 2 presents the data that was used to compile the inventory to represent the ‘construction’ stage.

Material	*Quantity (tonnes)*	*Supplier Location*	*Journey*	*Transport Type*	*Distance (km)*
CAISSONS					
Cement	2 900 000	Lafarge Cement UK (Aberthaw)	Aberthaw - Cardiff	Road	24
		CEMEX UK Operations (Rugby)	Rugby - Daventry	Road	18
			Daventry – Birmingham	Rail	80
			Birmingham - Wentlooge	Rail	182
			Wentlooge - Cardiff	Road	16
		Lafarge Cement UK (Cauldon)	Cauldon – Burton-on-Trent	Road	40
			Burton-on-Trent – Wentlooge	Rail	230
			Wentlooge - Cardiff	Road	16
Fine Aggregate	5 000 000	South Wales	St Bridas Bay - Cardiff	Road	167
		North Wales	Conwy - Cardiff	Road	309
		West Midlands	Market - Drayton	Road	248
		Glensanda	Glensanda Port - Cardiff	Ship	676
Coarse Aggregate	9 200 000	South Wales	Pembroke or Haverford West – Cardiff	Road	156
		West Midlands	Market Drayton - Cardiff	Road	248
		Glansanda	Glensanda Port - Cardiff	Ship	676
Rebar	900 000	Celsa UK	Tremorfa – Cardiff	Road	4
		Clwyd Rebar	Wrexham - Cardiff	Road	227
		Cogne Stainless Reinforcement	Rotherham - Cardiff	Road	326
TURBINES					
Equivalent to: Copper + Steel	43 200 + 388 800	Voith Hydro SL	Ibarra, Spain - Bayonne	Road	133
			Bayonne - Cardiff	Ship	999
		Voith Hydro AS	Trondheim, Norway - Bristol	Ship	2 050
		Alstrom Power	Grenoble - Marsailles	Road	307
			Marsailles - Bristol	Ship	3 410
EMBANKMENTS					
Rock	16 300 000	South Wales	Pembroke or Haverford West – Cardiff	Road	156
		Glensanda	Glensanda Port - Cardiff	Ship	676
Sandfill	29 100 000	From channel bed	n/a	n/a	0
Fabricated Steel	200000	unknown	n/a	n/a	0
ROADWORKS					
Roadworks	16.1 km	unknown	n/a	n/a	0

Table 2 Material requirements [7] with predicted suppliers and estimated methods and distances for transportation gate-to-site [10]

The highest impact components, and hence where sensitivity testing is appropriate, within the construction stage were identified as reinforced steel for embankments, caisson cement and rock for embankments. A range of alternative component representations were developed for these critical components in order to present a reasonable error margin.

4.1.2 'ON SITE' CONSTRUCTION ACTIVITIES

Roberts' study [8] remains the authority on assessing the resources and impacts associated with the construction activities, namely channel dredging, caisson tow out and caisson casting. The study offers total energy demand estimates for each activity based on their financial cost. Although none of the identified critical areas are based on Roberts' economic study, alternative inventory estimates were also generated for the on-site activities, in order to investigate the margin of error.

Channel Dredging: In 2008 the Crown Estate published estimates of 1.66 kg of fuel and 1.45 kg of fuel used per tonne of material dredged for two typical short-haul dredgers [19]. An estimate of the mass of material removed can by derived using a density approximation for each of the types of material. This mass value can then be used to estimate the total fuel required to dredge the channel for the Severn barrage construction. This calculation is summarised in Table 3.

Material Type	**Volume dredged [7] (m3)**	**Max density estimate (kg/m3)**	**Min density estimate (kg/m3)**	**Max mass dredged (t)**	**Min mass dredged (t)**	**Max fuel used, assuming vessel B (kg)**	**Min fuel used, assuming vessel D (kg)**
Sand	10 800 000	1 922 (34)	1 442 (34)	20 757 600	15 573 600	34 457 616	22 581 720
Rock	7 200 000	2 560 (35)	1 760 (35)	18 432 000	12 672 000	30 597 120	18 374 400
Total						*65 054 736*	*40 956 120*

Table 3 Calculation of fuel used in the dredging of the Cardiff-Weston barrage site

Tow Out: Spevack et al [10] suggests that the average towing distance from potential casting yards to barrage site is approximately 100km. The weight of each caisson is 126 000 [20] tonnes and there are known to be 175 caissons required which gives a total mass to be towed of 22 050 000 tonnes. Using these 2 pieces information, a range of tow out representations were generated using appropriate vessel types.

Caisson Casting: According to the ICE database [18], an additional energy figure of 0.51 MJ/kg should be added to any estimate for a concrete structure that is precast. This value can be used to recalculate an estimate for the energy consumed in the caisson casting:

$$22\,050\,000 \text{ tonnes of caisson} \times 0.51 \text{ MJ/kg of concrete cast} = 11\,245.5 \text{ TJ} \qquad (1)$$

4.2 OPERATION

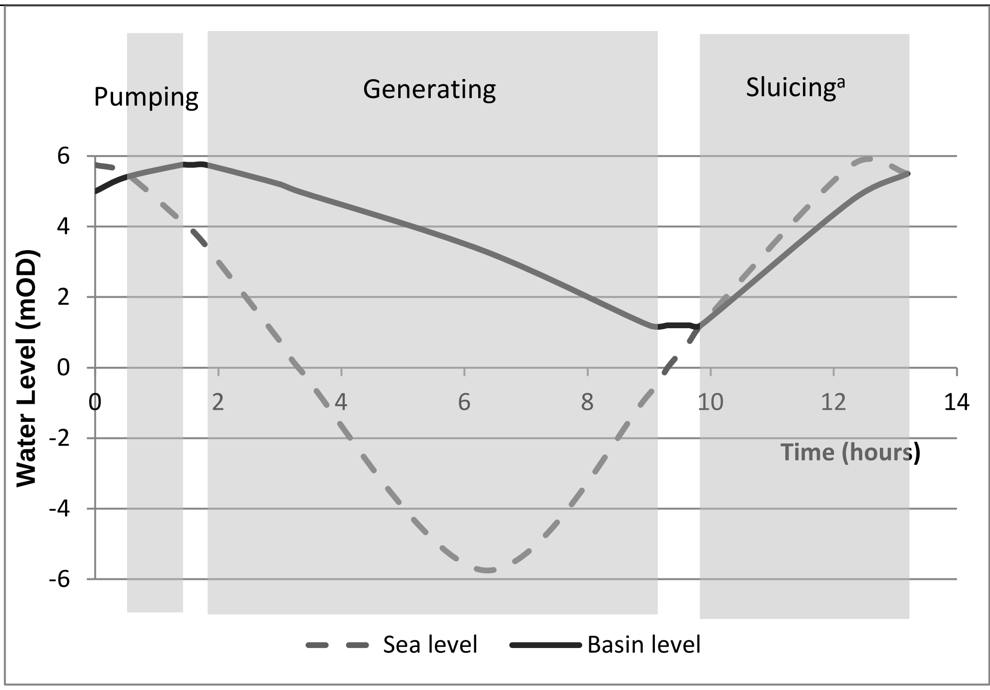
Roberts [8] assumes that operational costs would be 1.75% of capital costs per year and that the operational energy consumption could be calculated on the same basis, so assuming a 120 year lifetime, the operation stage would be 210% more expensive and, therefore, energy intensive than the construction stage, and hence the most significant of all the life stages, as shown in the Spevack et al [10] analysis. However, studies since Roberts' work have generally disregarded the operation stage entirely. Given this large variation in the assumptions applied, investigating the operation stage became a priority..

Energy and resource hungry operational processes were split into two main areas:

1. Direct processes: activities undertaken to directly enable power generation
2. Ancillary processes: energy and resources required for ancillary requirements for running the plant

Direct Processes: The only identified example of an energy hungry direct operational process is 'flood pumping'. The barrage turbines are such that plant will only generate when flow is from the basin out to sea and generation will be most efficient when the water level difference is greatest. At high tide the water level on the sea ward side of the barrage will be slightly higher than of the basin side. As the tide begins to ebb the sea level will drop until it equalises with the basin level. After the water levels have equalised the plant could begin to generate but, due to the very small water level differential, output will be very limited. In order to improve overall efficiency, it is often proposed that for some time following water level equalisation, the turbines should be operated in reverse and pump water from the sea ward side into the basin to increase the head before generation is allowed to begin. This is referred to as 'ebb generation plus flood pumping'

Previous barrage proposal have stated that the power required to power the turbines in pump mode would be bought from the grid and would not exceed 2 GW [21]. The power is bought from the grid as the barrage is not producing power during this point in the tidal cycle. The water level graph presented in Figure 3 shows that pumping would occur for 1 hour in every 12 hour tide cycle.



[a]**'Sluicing' is when the sluice gets are opened to allow the water to flow naturally from the seaward side back into the basin.**

Figure 3 Tide and Basin Levels, recreated from Figure 2.10 of the Severn barrage Project: General Report [5]

Hence, the maximum electricity demand from the grid for flood pumping over the barrage lifetime is:

$$120 \text{ years} \times 365.25 \text{ days} \times 2 \text{ hours} \times 2 \text{ GW} = 175 \text{ TWh} \quad (2)$$

Ancillary Processes: Quantitative data has been identified for the ancillary electricity demand only. When the plant is generating, this demand will be meet by the plant itself and is already accounted for in the annual net output estimate. However, the STPG report (1) states that, “For periods each day when the barrage is not generating, it will be necessary to purchase power to run the station auxiliaries and barrage general requirements. The annual mean load has been estimated at 19MW...”. Hence the total lifetime electricity demand, excluding that met by the plant itself, is:

$$120 \text{ years} \times 365.25 \text{ days} \times 24 \text{ hours} \times 19 \text{ MW} = 20 \text{ TWh} \quad (3)$$

Giving a total electricity demand estimate for the operation stage of the Severn Barrage of:

$$175 \text{ TWh} + 20 \text{ TWh} = 195 \text{ TWh} \quad (4)$$

It is necessary to list power bought from the grid as a separate inventory entry rather than deduct it from the net energy output from the plant as power from the grid is likely to have a very different energy demand profile and carbon intensity than that of the barrage itself.

If the barrage is opened in 2025 and operates for its full design life, it will be decommissioned around 2145 at the very earliest. So, over its lifetime, it will draw most of the electricity it requires to operate from a post 2050 National Grid. The UK aspiration is to reduce the carbon emissions of the nation grid considerably, in pursuit of meeting the target to reduce total UK emissions to 80% below 1990 base levels by 2050, and hence it is fair to consider the operational impact assuming that the grid reduces in impact. In order to estimate this, the operational impact was calculated assuming each of the options of grid mix set out in the Transition Pathway scenario modelling [22], i.e. that of the grid mix in 2050 in the Central Control, Market Rules and Thousand Flowers scenarios as described in the ‘Goal and Scope’ section. It is also feasible to assume a worst case future where measures to decarbonise the national grid fail and the environmental impact of the national grid reverts to 1990 levels, also modelled as part of the Transition Pathways work [22].

Figures 4 and 5 compare the estimates for energy demand and GWP generated using the two estimation methods, and show the potential range. The estimates based on electricity demand are, in general, considerably higher than those based on the Roberts method. It is only in the instance that the lowest carbon footprint National Grid is adopted, and only in the carbon assessment, that the two methods yield comparative results. As the Roberts estimate is based on cost only, the electricity demand method should be regarded as more representative and is adopted for the overall assessment.

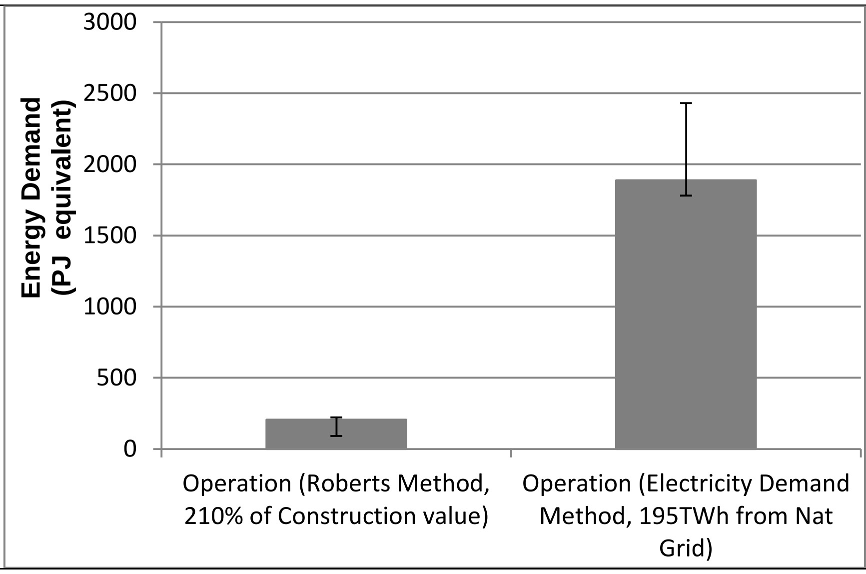


Figure 4 Comparison of energy demand estimates for barrage operation for each calculation method, including potential range

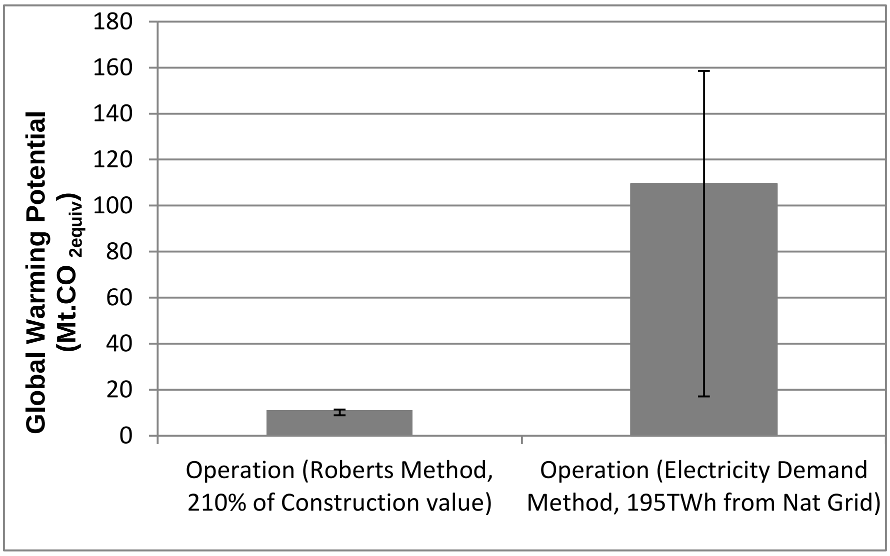


Figure 5 Comparison of GWP estimates for barrage operation for each calculation method, including potential range

4.3 MAINTENANCE

Consideration of the maintenance regime is restricted to the turbines only and represented by using estimates regarding the frequency and extent of their replacement. The environmental impact associated with the barrage maintenance is estimated to be equal to twice that of the total impact of the initial turbine instillation i.e. 100% every 40 years after construction over a 120 year life.

4.4 DECOMMISSION

Due to the long expected life of the barrage, the method of decommissioning and hence the associated environmental impacts is impossible to predict with any certainty. Therefore, the decommissioning stage is excluded from the assessment results, which is in-line with all other previous studies reviewed. However the end of life options and their impact relative to the other life stages can be speculated upon. The 120 year lifespan is dictated by the specification of the concrete which makes up the barrage itself, the turbines and other electrical components will of course need to be replaced within the 120 year lifetime and this is accounted for, see the above maintenance section. So, assuming that the barrage ceases to operate as an electricity generation plant after its 120th year, the three most likely options in ascending order of probable cost are as follows:

1. The plant is abandoned and allowed to disintegrate into the sea. This option would require no additional materials or energy. It could be polluting but comparable with impacts of disposal via landfill.
2. The barrage becomes an essential flood defence and/or road crossing and the structure is refurbished to prolong its life. This option would require both energy and material input but less than the original construction requirement.
3. The materials are removed from site and either recycled or sent to an inland landfill. This would require no additional materials, and would in fact provide materials in the recycling scenario. It is estimated that the UK currently recycles 22% of demolition waste and initiatives are in place to increase this percentage [23]. However the complete removal of the barrage from site would require at least as much energy and emit as much carbon as the ‘on site’ activities of construction, plus the transportation of the spoils to either a recycling centre or landfill would have some associated energy and carbon impacts.

It seems unlikely that any of the above options would exceed the energy requirements or the carbon footprint of the construction stage. Hence, it can be estimated that whichever option is adopted, the decommission stage will be of less significance to the overall impact of the Severn barrage than the construction stage.

5 RESULTS AND DISCUSSION

5.1 ENERGY ANALYSIS

Figure 6 shows the total energy demand estimate for the three modelled life stages of the barrage. The error bars show the potential variation depending on the assumptions made in the LCA inventory. It can be seen that, by far, the most energy intensive stage of the barrage lifetime is the operation stage. The total energy demand for these three life stages is estimated to be 1,986,800 TJ, in a possible range error of between 1,825,500 TJ – 2,537,400 TJ.

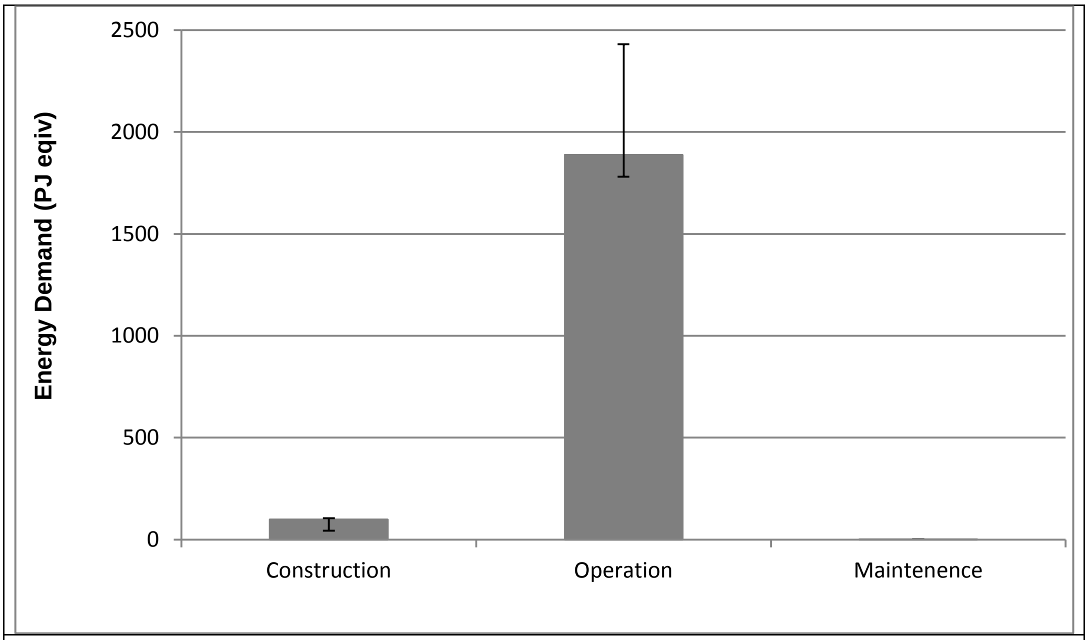


Figure 6 Energy demand of the Severn barrage by life stage, including the possible range of scores

This estimate is an approximately 6 times larger than that estimated by Spevack et al [10]. Table 4 compares the results with Spevack et al. The large difference can be entirely attributed to the different assumptions adopted for the estimation of the operation stage i.e. that the Spevack et al [10] analysis is based on percentage assumption taken from Roberts' work as opposed to the re-estimate based on the electricity demand figures provided by the STPG [5]report. Roberts provides little justification for his assumption and it is not expressly clear what operational processes are included. Importantly, the more thorough inventory analysis suggests that Roberts method yields an underestimate.

	Construction Energy (TJ)	**Operation Energy (TJ)**	**Maintenance Energy (TJ)**
Spevack et al [10]	101 130	212 360	15 120
Kelly et al	98 460	1 887 870	490

Table 4 Comparison of energy estimates by life stage

Table 5 shows the total estimated lifetime energy demand, the energy payback period and the energy gain ratio for the Severn barrage, with a range of error based on the alternative model inventories. These figures are far less favourable than those found in the existing literature. Neither the Roberts nor the Spevack et al studies expressly say whether the power demand for flood pumping is included in their percentage estimate. However, the modelling studies reviewed [7][21] suggest that the assumed power output of 16.8 TWh in the case of Spevack et al would not be obtained without flood pumping, therefore the study results must be regarded as inclusive of flood pumping. The Roberts study was completed before the subtleties of operational modes had been explored, however the similarities between the Roberts results and the Spevack et al results imply that it is justified to regard the Roberts results as being inclusive of flood pumping. Hence the differences here can also be accounted for by the increased detail in the operation energy estimate in comparison to studies that have been completed previously.

	Year of Study	Energy Demand (TJ)	Energy Gain Ratio	Energy Payback Period (Years)
Roberts (1982) [8]	1982	358 000	12 – 16	8.3
Spevack et al [10]	in press	328 610	18 – 26	8.6
Kelly et al, with flood pumping (Range of error)	2011	1 986 800 (1 825 500 – 2 537 400)	3.6 (2.8 – 4.0)	33 (30 – 42)

Table 5 Summary of energy results from existing analyses

Figure 7 compares the specific energy demand, energy demand per generated unit (1kWh), for the Severn barrage, including a range of error, and for the five considered options for the energy demand of the National Grid mix [22]. All estimates for the Severn barrage are considerably less than any of the estimates for the National Grid, despite the increase in lifetime energy demand in comparison to previously published results.

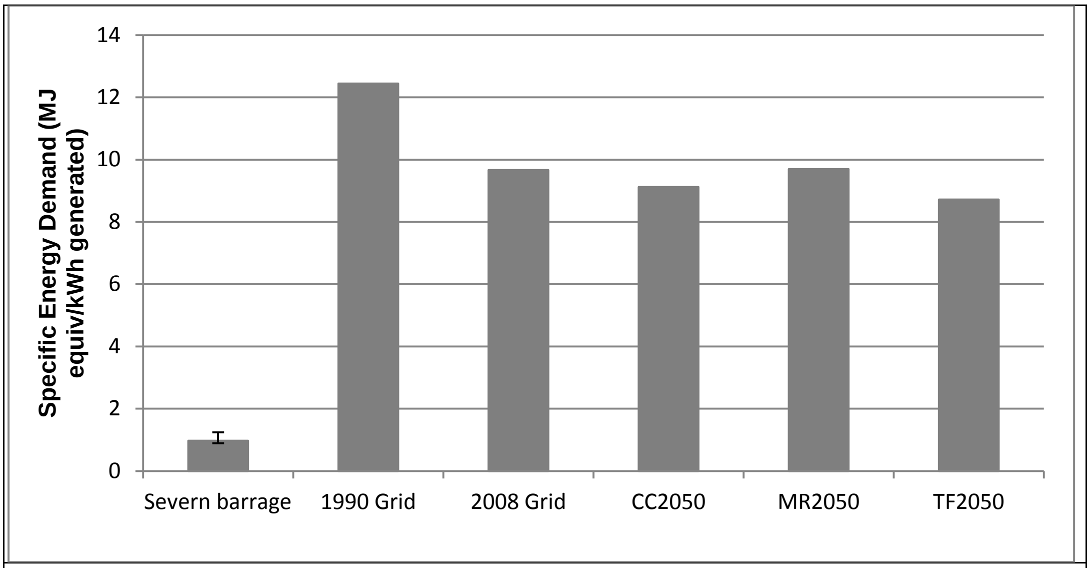


Figure 7 Comparison of specific energy demand (MJ equivalent per kWh generated) for electricity output from the Severn Barrage, including possible range of scores, with electricity from possible UK National Grid Mixes

5.2 CARBON ANALYSIS

Figure 8 shows the total GWP estimate for the three modelled life stages of the barrage. The error bars show the potential variation depending on which inventory options are selected. As might be expected, the proportional distribution of the carbon (equivalent) emissions across life stage echoes that found in the energy analysis and the largest contributor is the operation stage, however the range of error is much larger. The total carbon emission is estimated at 115Mt.CO_2 (equiv) but the range of error stretches from 21Mt.CO_2 (equiv) to 164Mt.CO_2 (equiv). For reference, that is approximately between 1 and 8 times that of the Spevack et al estimate and between 4 and 33 times that of the SDC estimate.

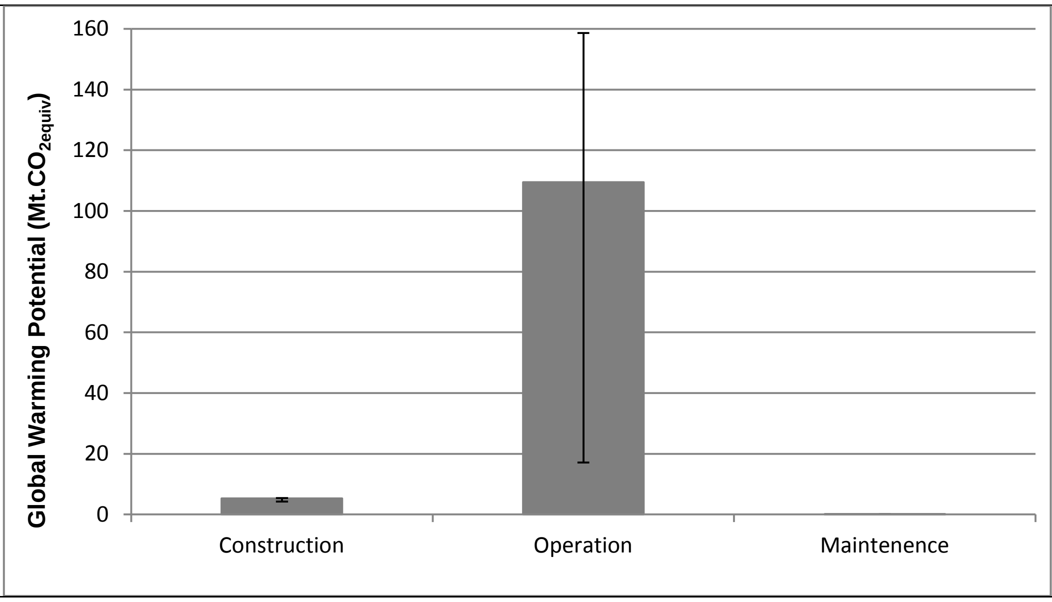


Figure 8 GWP (Mt.CO_2 equiv) of the Severn barrage by life stage, including the possible range of scores

The emissions at the operation stage, the largest contributor, are entirely accountable to electricity drawn from the National Grid so the estimate depends on what National Grid Mix is assumed. Table 6 compares the energy demand and carbon emitted per generated unit (kWh) for a range of representations for the UK National Grid Mix provided by work carried out by the Transition Pathways Consortium research [22]. This demonstrates that the carbon emissions associated with 1kWh of electricity varies more than the energy demand depending on what National Grid Mix is adopted, and hence why the total carbon estimate for the Severn barrage has a much wider range of error than that of the energy estimate.

	1990 Baseline	**2008**	**2050 – Central Control**	**2050 – Market Rules**	**2050 – Thousand Flowers**
Specific Energy Demand (MJ/kWh)	12.5	9.7	9.1	9.7	8.7
Specific Carbon emissions (g.CO2equiv/kWh)	812.2	560.4	87.5	111.8	96.5

Table 6 Specific energy and carbon estimates for different representation of the UK National Grid Mix

Table 7 presents a comparison of the carbon analysis result with the results of the existing studies reviewed for background. It can be seen that the specific carbon estimates are much higher and the displaced carbon payback periods are longer than those predicted by previous studies. Neither the SDC [7] nor the Shawater [9] studies make any attempt at a detailed estimate for operational emissions, however both studies adopt net power output figures of 17 TWh implying that their results should be comparable with a study which is inclusive of flood pumping. The much higher carbon estimates and the longer displaced payback periods predicted here highlight the importance of including an estimate for the operation stage, and the consequences of dismissing it as minimal or nil.

	Year of Study	Carbon Emitted (Mt.CO2 equiv)	Specific Carbon emissions (g.CO2 equiv/kWh)	Displace Carbon Payback Period wrt Nat Grid (years)
SDC [7]	2007	5	2.42	0.68
Shawaer [9]	2009		5.7	<0.5
Spevack et al [10]	in press	19	9.5-11.0	
Kelly et al, with flood pumping (Range of error)	2011	115 (21 – 164)	56.2 (10.5 – 80.4)	9.1 (1.6 – 20.5)

Table 7 Summary carbon results from existing analyses

Figure 9 compares the estimates for the specific GWP from each of the National Grid mix options with the estimate for the Severn barrage, including a range of error. For all National grid options, the carbon (equiv) emitted per kWh exceeds that of even the worst case estimate for the Severn barrage. This suggests that the electricity generated by the Severn barrage will provide a carbon saving in comparison with the National Grid, at least until 2050, despite the increase in operational carbon intensity.

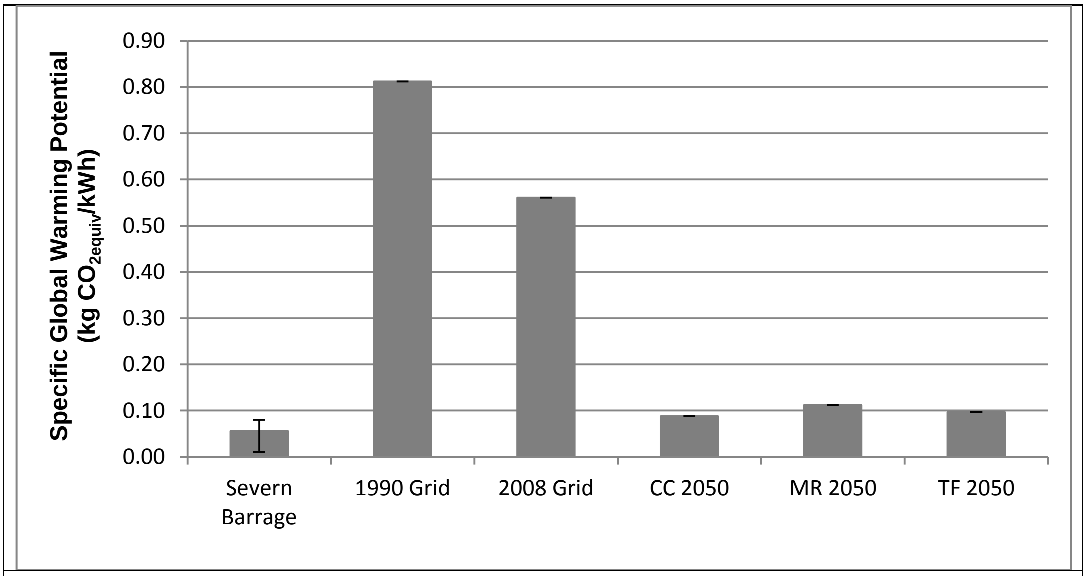


Figure 9 Comparison of specific GWP (kg.CO_2 equiv per kWh generated) for electricity output from the Severn Barrage, including possible range of scores, with electricity from possible UK National Grid Mixes

5.2.1 RESULTS IN THE CONTEXT OF UK CARBON REDUCTION TARGETS

It is estimated that the Severn barrage scheme could meet 0.6% of the total UK energy supply [6]. Hence in order to assess whether the scheme is appropriate in the 2050 decarbonised ideal, the embodied carbon per year must be compared to 0.6% of the ideal 2050 energy supply emissions. The UK energy supply sector’s green house gas emission was 288Mt.CO_2 (equiv) in the base year 1990 [24]. The UK target is to reduce emissions to 80% below 1990 levels by 2050 [1]. This means that the energy supply sector will have to reduce its emissions to 58Mt.CO_2 (equivalent) per year. Hence the target carbon emission per year for the Severn barrage scheme is given by:

$$0.6\% \times 58 \text{ Mt.CO}_2 \text{ (equiv)} = 0.35 \text{ Mt.CO}_2 \text{ (equiv)} \qquad (5)$$

The lifetime carbon emissions per year for the primary model of the Severn barrage scheme is given by:

$$115 \text{ Mt.CO}_2\text{(equiv)} / 120 \text{ years} = 0.96 \text{ Mt.CO}_2\text{(equiv)/year} \qquad (6)$$

This figure does exceed the target carbon emission per year. However, as discussed above, because the main contributor to the overall impact of the Severn barrage plant is electricity drawn from the national grid, when making comparisons with the overall UK supply it is only a fair to use the plant representation which is based on the same network mix. Assuming that the electricity is supplied by the least carbon intensive grid representation, i.e. the ‘Central Control’ scenario result taken from the Transition Pathways work which actually does not meet the 80% reduction, the carbon emissions per year of life for the Severn barrage scheme fall well below the target carbon emission per year, and are calculated thus:

$$21 \text{ Mt.CO}_2\text{(equiv)} / 120 \text{ years} = 0.18 \text{ Mt.CO}_2\text{(equiv)/year} \qquad (7)$$

6 IMPROVEMENT ANALYSIS: EXCLUDING FLOOD PUMPING

The largest contribution to both energy demand and carbon intensity is accountable to the operation stage of the barrage life and this is therefore the area where the greatest improvements can be made. The impact of the operation stage is mainly a result of the electricity bought from the grid to drive the flood pumping operation. However, it is not a certainty that the flood pumping would be included in the barrage operational regime. Hydraulic modelling (0-D) completed by the STPG in 1989 found that flood pumping could lead to a 9.7% increase in energy output over ebb generation only and therefore concluded that flood pumping was required [21]. More recent modelling carried out for the SDC study estimated that gains from flood pumping could be 10.3% when repeating the STPG modelling method (0-D), however, when more sophisticated techniques (1-D and 2-D) were applied gains were estimated to be as low as 3.2% and 2.7% [7]. To the nearest TWh, however, it can be assumed that the average annual output in ebb generation only mode would be 16 TWh, giving a lifetime output figure of 1920 TWh, which means that 175 TWh of power input from the grid leads to only 120 TWh of power output from the barrage. This simplified calculation implies that ebb generation mode only would be optimal. Further impact analysis was carried out to assess the effect of changing the barrage operational mode.

6.1 ENERGY ANALYSIS

Figure 10 shows the energy demand for the Severn Barrage scheme across the life stages of construction, operation and maintenance, under the assumption that no flood pumping is employed in operation. Removing the energy required for flood pumping in the operation stage has reduced the energy demand by approximately a factor of 10 to 193,193 TJ, which is now comparable to the Spevack et al estimate. The overall plant energy demand is reduced to 292,138 TJ, with a range of 226,555 – 355,411 TJ. However, the operation stage does remain the most energy intense stage and is still wholly attributable to power drawn from the grid. Clearly, improvements to the remaining plant operations to reduce power demand will still have a far greater effect on the overall demand than design choices made in the construction or maintenance stages, no matter what the energy profile of the grid.

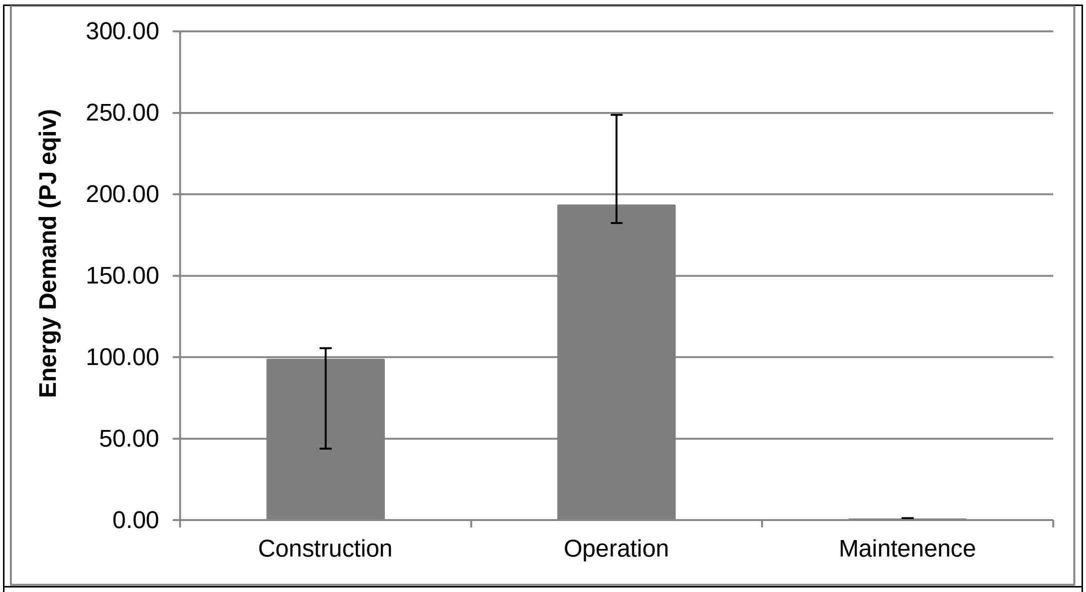


Figure 10 Energy demand of the Severn barrage without flood pumping by life stage, including the possible range of scores

The energy gain ratio for the plant assuming ebb generation only is calculated at 23.9, with a range of 19.7 – 30.8, and the energy payback period is 5 years, with a range of 4 – 6 years. This much improved figures support the case that, from an energy optimisation point of view, flood pumping should not be employed.

6.2 CARBON ANALYSIS

Figure 11 shows the GWP estimate for the three modelled life stages of the barrage, under the assumption that no flood pumping is employed. As might be expected, a reduction in the operational carbon intensity is seen of a similar magnitude that of the reduction in energy demand of almost 10 fold, giving a operational green house gas emission estimate of 11.2 Mt.CO_2 (equiv). The huge range however, still demonstrates the dominate effect that the carbon intensity of the National Grid itself has on the overall impact of the plant.

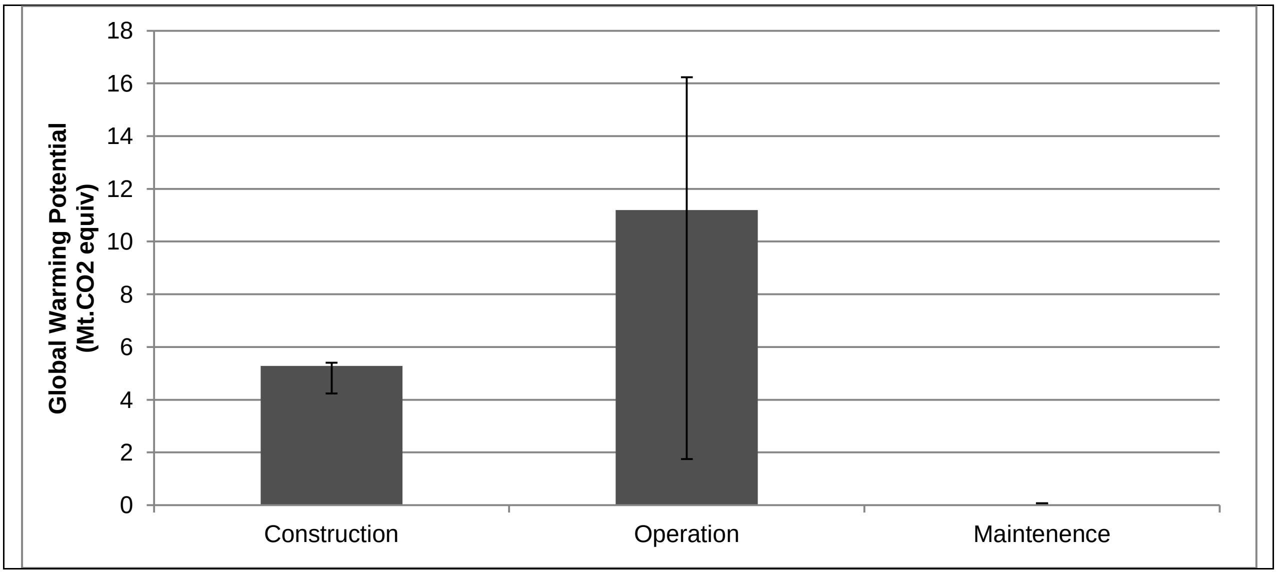


Figure 11 GWP (expressed in Mt.CO_{2equiv}) of the Severn barrage without flood pumping by life stage, including the possible range of scores

The total plant green house emissions are estimated at 17 Mt.CO_2 (equiv), with a range of 6 – 22 Mt.CO_2 (equiv). The specific carbon emissions of power output from the plant are estimated at 8.6 g of CO_2 (equiv), with a range of 3.1 – 11.3 g of CO_2 (equiv), and the displaced carbon payback with respect to the National Grid would be 1.3 years, with a range of 0.5 – 4.4 years. Again, these results are comparable with the Spevack et al result and also with the Shawater results, see Table 7, although they shouldn't be as these studies use annual power outputs that necessarily assume that flood pumping *is* included. These results are still significantly more than the SDC estimate.

6.2.1 CONTRIBUTION TO UK CARBON REDUCTION TARGETS

The lifetime carbon emissions per year for the primary model of the Severn barrage scheme assuming ebb generation only is given by:

$$17 \text{ Mt.CO}_2\text{(equiv) / 120 years} = 0.14 \text{ MT.CO}_2\text{(equiv)/year} \quad (8)$$

This figure already falls well below the carbon target for 0.6% of UK energy in 2050. Assuming that the electricity is supplied by the least carbon intensive grid representation, i.e. the 'Central Control' scenario result taken from the Transition Pathways, the lifetime carbon emissions per year for the Severn barrage scheme assuming ebb generation only is given by:

$$6 \text{ Mt.CO}_2\text{(equiv) / 120 years} = 0.05 \text{ Mt.CO}_2\text{(equiv)/year} \quad (9)$$

7 CONCLUSIONS

The assessment has shown that the energy and carbon intensity of the Severn barrage is small in comparison to the National Grid mix. It has also shown that, given reasonable assumptions, the Severn barrage can contribute to meeting the UK carbon reduction target of 80% below 1990 levels by 2050. Whilst the Severn barrage has been used as a case study, it is proposed that the results can be taken as an indicative measure of the performance of any proposed barrage both nationally and internationally.

Significantly, the assessment has shown that the operation stage of the Severn barrage is the largest contributor to the total environmental impact of the plant over its lifetime, whether flood pumping is included in the inventory or not. This finding is in stark contrast to the conclusions of the SDC [7] and Shawater [9] studies which both dismissed the operation stage as having minimal impact without any detailed assessment. The Roberts [8] and Spevack et al [10] studies, the latter being largely based on methods from the former, both showed that the operation stage was the largest contributor.

The overall impact estimates made are considerably larger than estimates made in any other study so far. The large difference can be entirely attributed to the more thorough approach adopted for the estimation of the operation stage i.e. the re-estimate of the operational electricity requirement based on demand figures taken from the STPG [5] report. This finding demonstrates that the impact of the plant is most sensitive to improvements in the operation stage of its life. The largest improvement to the impact of the operation stage can be made by removing the electricity demand for 'flood pumping'.

Although this will lead to a slight reduction in net power output, the analysis has shown that, from an impact point of view, the disadvantages of removing flood pumping are far out weighted by the advantages and that ebb generation only should be the adopted operational regime.

However, even without flood pumping, the impact of the plant operation will still dominant over its lifetime. In terms of energy demand, it seems the operational stage will always dominate, although further improvements could be investigated via efficiency measures for other operational activities.

The exclusion of flood pumping alone would secure the barrages contribution to reaching the UK carbon reduction targets. However, the carbon analysis demonstrates that by far the largest proportional improvements are made via improvements in the National Grid Mix itself. This would have the potential to reduce the operational impact to below that of the construction. So, rather satisfyingly, the most effective approach to improve the Severn barrage's carbon intensity would be to identify and enable low other low carbon technologies which can contribute to the future National Grid mix, which is, in fact, the one of the prime directives of the UK 'sustainable energy' movement, including the Transition Pathways Consortium.

The work highlights the impact of tidal barrages in general and concludes that where there is an operational electricity demand, the carbon intensity of the grid mix taken to meet the demand is critical to the overall impact of the system. Therefore, when such schemes are analysed it is crucial that they are not done so in isolation, but in conjunction with a wider knowledge of any associated power inputs to the system.

8 ACKNOWLEDGMENT

The research reported here was supported by the Transition Pathways project, co-funded by the UK Engineering and Physical Sciences Research Council (EPSRC) and E.ON UK, (Grant Ref: EP/F022832/1) and a studentship provided by the University of Bath. The authors would also like to thank the anonymous reviewers for their input and comments.

9 REFERENCES

[1]. **Her Majesty's Government.** Climate Change Act. *The National Archives.* [Online] 2008. [Cited: 23 09 2010.] http://www.legislation.gov.uk/ukpga/2008/27/contents.
[2]. **Her Majesty's Government** Renewables Obligation. *Department of Energy & Climate Change.* [Online] [Cited: 06 10 2010.] http://www.decc.gov.uk/en/content/cms/meeting_energy/renewable_ener/renew_obs/renew_obs.aspx.
[3]. **Department of Energy.** *Tidal Power from the Severn Estuary.* UK : Her Majesty's Government, 1981.
[4]. **Severn Tidal Power Group.** *Tidal Power from the Severn.* UK : Her Majesty's Government, 1986.
[5]. **Severn Tidal Power Group and the Department of Energy.** *Severn Barrage Detailed Report.* UK : Her Majesty's Government, 1989.
[6]. **Sustainable Development Commission.** *Turning the Tide: Tidal Power in the UK.* UK : Sustainable Development Commission, 2007.
[7]. **Black & Veatch.** *Research Report 3 - Severn barrage proposals.* UK : Sustainable Development Commission, 2007.

[8]. **Roberts, F.** *Energy Accounting of River Severn Power Schemes.* s.l. : Applied Energy 11, pp 197-213, 1982.
[9]. **Woollcombe-Adams, C, Watson, M and Shaw, T.** *Severn Barrage tidal power project implications for carbon emissions.* UK : Water and Environment Journal 23, pp 63-68, 2009.
[10]. **Spevack, R, Jones, C and Hammond, G.** *Technical Assessment of Two Tidal Power Barrage Schemes Across the River Severn.* UK : University of Bath, 2011.
[11]. **Standards Policy and Strategy Committee.** *Environmental management - Life cycle assessment - Principles and framework.* s.l. : British Standard, 2006. BS EN ISO 14040:2006.
[12]. **Standards Policy and Strategy Committee .** *Environmental management - Life cycle assessment - Requirements and guidelines.* s.l. : British Standard, 2006. BS EN ISO 14044:2006.
[13]. **PRé Consultants.** *SimaPro 7.3.* Netherlands : PRé Consultants, 2010.
[14]. **Frischknecht, R and Jungbluth, N.** *Implementation of Life Cycle Impact Assessment Methods: Cumulative Energy Demand (CED).* s.l. : EcoInvent, ESU-services Ltd. and the Swiss Centre for LCI, 2003.
[15]. **International Panel on Climate Change.** *IPCC 2007 GWP: Fourth Assessment Report.* s.l. : International Panel on Climate Change, 2007.
[16]. **Foxon, T J, Hammond, G P and Pearson, P J G.** *Developing transition pathways for a low carbon electricity system in the UK.* s.l. : Technological Forecasting & Social Change, Vol.77, No.8, pp 1203-1213, 2010.
[17]. **Inventories, Swiss Centre for LCI.** *EcoInvent.* Switzerland : EMPA, 2010.
[18]. **Hammond, G and Jones, C.** *Inventory of Carbon and Energy.* UK : University of Bath, 2010.
[19]. **Kemp, R.** *Marine Estate Research Report: Energy Consumption of Marine Aggregate Extraction.* s.l. : Crown Estate, 2008.
[20]. **Severn Tidal Power Group and Department of Energy .** *Severn Barrage Project Detailed Report Vol IIIA: Civil Engineering including Site Investigations.* UK : Her Majesty's Government, 1989.
[21]. **Severn Tidal Power Group and the Department of Energy.** *Severn Tidal Barrage Project Detailed Report Vol II: Electrical and Mechanical Engineering.* UK : Her Majesty's Government , 1989.
[22]. **Hammond, G, Howard, H and Jones, C.** *The Energy and Environmental Implications of More Electric UK Transistion Pathways: A Whole System Perspective.* UK : Energy Policy, In Press.
[23]. **Everett, Cath.** Concrete must not go to landfil, warns experts. *Business Green.* [Online] July 2009. [Cited: 02 August 2011.] http://www.businessgreen.com/bg/news/1807224/concrete-landfill-warn-experts.
[24]. **National Statistics.** UK Emission Statistics. *Department of Energy & Climate Change.* [Online] [Cited: 01 06 2011.] http://www.decc.gov.uk/en/content/cms/statistics/climate_stats/gg_emissions/uk_emissions/uk_emissions.aspx.